1959

Visualization of two dimensional fluid flow patterns using streaming double refraction

Linde, David J.; Webster, William L.

Massachusetts Institute of Technology

VISUALIZATION OF TWO DIMENSIONAL FLUID FLOW PATTERNS USING STREAMING DOUBLE REFRACTION

DAVID J. LINDE
AND
WILLIAM L. WEBSTER

VISUALIZATION OF TWO DIMENSIONAL FLUID FLOW PATTERNS USING STREAMING DOUBLE REFRACTION

by

DAVID J. LINDE, LIEUTENANT, U.S. COAST GUARD

B.S., U.S. Coast Guard Academy (1952)

and

WILLIAM L. WEBSTER, LIEUTENANT, U.S. COAST GUARD

B.S., U.S. Coast Guard Academy (1950)

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS

FOR THE DEGREES OF NAVAL ENGINEER AND MASTER OF SCIENCE

IN NAVAL ARCHITECTURE AND MARINE ENGINEERING

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

25 May 1959

Signatures of Authors: ______________________________

Department of Naval Architecture
and Marine Engineering,
25 May 1959.

Certified by: ______________________________
Thesis Supervisor

Accepted by: ______________________________
Chairman, Departmental Committee
on Graduate Students

VISUALIZATION OF TWO DIMENSIONAL FLUID FLOW PATTERNS USING STREAMING DOUBLE REFRACTION, by David J. Linde and William L. Webster. Submitted to the Department of Naval Architecture and Marine Engineering on 25 May 1959 in partial fulfillment of the requirements for the degree of Naval Engineer and the degree of Master of Science in Naval Architecture and Marine Engineering.

ABSTRACT

The object of this thesis was the design and construction of a fluid flow facility which would be useful in the qualitative study of two dimensional or three dimensional fluid flow problems. In addition to its applicability in comparative or feasibility type investigations, it may be used as a visual aid to classroom study of hydrodynamics.

The test technique uses the double refracting properties of a dilute solution of hectorite coupled with a circularly polarized field of light in order to "visualize" fluid flow.*

The usefulness of this facility was demonstrated by the conduct of a brief study of the effectiveness of various types and arrangements of turbulence stimulators. The principal result of these tests is the indication that the trip wire device located at a specified distance from a boundary is an excellent turbulence stimulating device. Other indications are that a vertical row comprised of a moderate number of small diameter pins is comparatively quite good; that sand strips, both vertically and horizontally located, are less effective; and that grooves and cavities are definitely not effective in producing turbulence.

In order to fully substantiate the findings and to discover the most effective stimulator per unit of parasitic drag, it is necessary to amplify the tests. An extension of the tests should include a wider range of total projected or flat areas of the devices and greater variation in their arrangements.

Thesis Supervisor: J. Harvey Evans

Title: Associate Professor of Naval Architecture

---

* Refer to pages 4 through 6 of the introduction for a discussion of "visualization" of flow.

ACKNOWLEDGMENT

The authors wish to express their appreciation to:

Professor J. Harvey Evans, of the Department of Naval Architecture and Marine Engineering, who acted in the capacity of thesis supervisor and directed us to this field of work.

Professor James W. Daily, of the Department of Civil Engineering, who assisted us greatly in the field of hydrodynamic flow and reviewed the design of our test facility.

Mr. Selwyn Blake, of the Department of Naval Architecture and Marine Engineering, for his technical advice and assistance in constructing parts of the test facility.

TABLE OF CONTENTS

INTRODUCTION

The main portion of the effort in this thesis was directed at designing and constructing a test facility for studying fluid flow. It is envisioned that this facility can be used for hydrodynamic flow research in the future. The experimental study conducted in this thesis was aimed at indicating the type of studies which could be conducted with this test facility.

Some fluid flow facilities which employ the technique of streaming double refraction have been built and used. Facilities on which detailed information exists can be found in references 9 and 10. Unfortunately these facilities, which were used to determine whether or not a quantitative flow analysis could be made, have been dismantled. Other facilities have been or are being used in qualitative studies of flow. The California Institute of Technology and The Newport News Shipbuilding and Dry Dock Company have done work in this field. However, very little information regarding the design of these "channels" or the test work performed with them was made available.

A detailed account of the design considerations and the construction of the facility developed in this thesis appears in Appendix A.

In order to comprehend the complex nature of hydrodynamic flow much experimental work has been done. To date the beginnings of such work it is usual to recall that in 1856 Osborne Reynolds performed his classic experiments on the transition of flow from laminar to turbulent. A thin stream of ink injected into a large flow of water was used as the indicator.

Since then many variations on the ink stream have been used as "tell tails" of what is happening in fluid flow. Generally these materials are small gas bubbles, small liquid droplets, thin colored liquid streams, thin threads, or small macroscopic particles. The gas bubble, liquid droplet and thin stream methods are ineffective once the flow becomes turbulent. The methods of visualization which depend upon threads or the visibility of foreign particles of macroscopic size are at a serious disadvantage because such materials cannot follow the intricate paths of rapidly changing flow. Additionally, they, like some of the foregoing methods, produce a non-Newtonian type of flow.

The technique of streaming double refraction, while usually requiring a more elaborate test facility than methods mentioned previously, has certain advantages. These advantages are that the flow patterns can still be distinguished after the onset of turbulence and that the small platelets of the suspended material are able to closely follow fluid motion.

Double refraction occurs in a stream when a velocity gradient is set up in a fluid which has certain properties. The required properties are that the fluid be a colloidal suspension of an anisometric and submicroscopic material. A colloidal suspension of purified hectorite has such properties.[9,10,21]

This purified hectorite, essentially magnesium silicate, is a clay of the montmorillonite type. When completely dispersed in water the hectorite particle is roughly 700 millimicrons long, 70 millimicrons wide, and 1 millimicron thick. These particles are so small that they must be shadow photographed by means of an electron microscope.[17] Because of their small size these particles do not settle out under the influence of gravity. Also, as a consequence of their small size, flow of a sufficiently dilute solution of hectorite can be said to closely approach, if not be, a Newtonian type of flow.[9,10,21,27] In addition to the satisfactory particle size a dilute suspension of hectorite (less than about 1.25% by weight) possesses other good properties. These properties are that it has a viscosity, surface tension, and density close to that of water.[6] An important point in regard to the viscosity is that for a dilute suspension the viscosity is almost constant for varying shear rates. The above is not true for a highly concentrated solution.[6] Furthermore a dilute suspension

has a high sensitivity (this means that the shear patterns are distinct), a quick relaxation time (this means that rapid changes in the flow patterns are discernible), and good light transmission qualities.[21] Certain minor disadvantages must be considered. These are that not all materials are inert to hectorite and that the solution is quite slippery.

Because of the shape of the hectorite particle, its long dimension tends to become aligned in the direction of flow. This action on the part of a large number of particles produces the effect of streaming double refraction.[21]

Double refraction is the property of a substance which causes an electromagnetic vibration, hereafter referred to as a light ray, which is incident upon this substance to be separated into two distinct rays. These rays are plane polarized, one in the optic axis of the substance or particle, and the other perpendicular to the optic axis. The ray parallel to the optic axis is called the extraordinary ray, the other ray is called the ordinary ray. The indices of refraction of the two rays are different (this difference is called the degree of double refraction). Since the velocity of light is a function of the index of refraction, the velocity of light along the ordinary axis differs from that along the extraordinary axis. This difference in velocities produces a phase shift in the emergent

light. Interference, both constructive and destructive, results from the phase shift and causes variations in the intensity of the emergent light.

When the above described property is used in conjunction with a field of circularly polarized monochromatic light, a pattern, which is dependent upon the amount of double refraction existing in various parts of the area under study, results. Circularly polarized light is used because the observed intensity of the emergent light is independent of the orientation of either the polarizing system or the analysing system with respect to the double refraction medium or each other. Such is not the case if plane polarized light is used. In addition the intensity of emergent light is greater for the circularly polarized light than for the plane polarized light.[13]

Basic to the following discussions is the consideration that the physical characteristics of a solution and its temperature are maintained constant. It is assumed that the optic axis of the hectorite platelet is along the long dimension of the platelet.[9,10] In the presence of a velocity gradient the long dimension of the platelets tend to line up at a certain average angle to the plane of maximum shear in the fluid. The number of particles so aligned is also dependent upon the existing velocity gradient. Thus a certain amount of double refraction exists in each part

of the flow. In the presence of monochromatic circularly polarized light these amounts of double refraction show up as a varying pattern of light and dark lines - much the same as the fringes in a photoelastic study. However, the relationships between the streamlines and the planes of maximum shear must be considered. First a definition: the extinction angle is usually defined as the angle between the optic axis (the long axis) and the streamline.[21] Actually from its use in analyses it is apparent that the angle between the optic axis and the plane of maximum shear is of principal significance. Because previous experimenters had obtained the relationship between the extinction angle and velocity gradients by means of a Kundt cell (parallel flow) the discrepancy was not noticed.[21] The reason for this is that for parallel flow the planes of maximum shear and the streamlines are coincident. However, for convergent and divergent flow the planes of maximum shear and the streamlines are not coincident. The quantitative evaluation of flow by means of streaming double refraction awaits the determination of the extinction angle as a function of velocity gradient and type of flow, (convergent, divergent, or parallel). Such work is beyond the scope of this thesis. Despite these shortcomings the use of streaming double refraction for qualitative flow analysis possesses merit.

Experimenters in the field are certain that the lines of shear may be generally assumed to closely coincide with the actual streamlines.[26,27] More important than this is that valuable information such as where flow separation occurs, where flow reversal takes place, where turbulence is initiated, and the amount of turbulence which is caused - all of these may be obtained through the use of streaming double refraction.* These qualities are most useful in qualitative type of studies where a comparison is to be made among several designs or where a design feasibility study is required. The evaluation of the effectiveness of various types of turbulence stimulators is one such study; it is the experimental subject of this thesis.

The study of turbulence stimulation on ship models and on various geometrical shapes has been undertaken by many individuals and by several establishments. The David Taylor Model Basin (DTMB) has reported several of these studies[3,4,7] concerning the use of turbulence stimulators on ship models.

One method used by DTMB for the detection of laminar and turbulent boundary layers is the hot wire method. This means of detection does not at the present measure the intensity of turbulence.[4] The reports of DTMB are based

---

* In addition a fair idea of the flow can be obtained visually when the flow condition is turbulent. This is because the eye can distinguish quite readily the difference between the persisting patterns of the main flow and the continuously changing patterns of the turbulence. Also the double refraction technique is of some value in the design of three-dimensional bodies. (26)

on the use of sand strips, trip wires and rods with the latter placed ahead of the ship model. The conclusion reached is that the use of a trip wire or a rod gives the best turbulence stimulation.[4] Comments on various technical papers on this subject strongly indicate that an extensive study on the use of pins for turbulence stimulation has been undertaken at DTMB. However, there appears to be no published results of this study.

The Department of Scientific and Industrial Research, Ship Division, National Physical Laboratory, Teddington, England, has also undertaken studies in this field. It has experimented with the use of chemical coatings on the hulls of ship models for the detection of turbulent boundary layers.[25] These chemical coatings are rapidly dissolved by a turbulent boundary layer but only slowly dissolved by a laminar boundary layer. A separate study at this facility[2] evaluated the results of various tests with stimulators by measurement of towed model resistance.

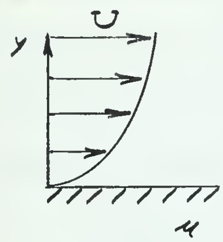
The conclusions reached are that pins or a trip wire are acceptable as turbulence stimulators and are superior to sand strips and rods. Of the two acceptable methods the former is preferred because of the ease of installation and of maintenance of position. The recommended array consisted of a few pins of moderate diameter rather than of many pins of small diameter.[2]

Both of the above establishments have experimented with the method of dye injection into the boundary layer for detection of the type of boundary layer present. There are available some very good pictures of this method in use.[2]

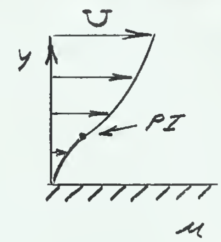
The Webb Institute has conducted a rather exhaustive study on turbulence stimulation for a trawler hull form series.[20] This study was conducted using sand strips, trip wires, pins, vibrators and struts. The latter two methods performed very poorly and are not recommended for use especially on low-speed models. The recommendation of the study was highly in favor of the use of pins for turbulence stimulation.

The National Advisory Committee for Aeronautics (NACA) has conducted several investigations in wind tunnels on the effect of certain shapes and hollows on the transition from a laminar boundary layer to a turbulent boundary layer in air flowing past various airfoils and geometrical shapes. Theoretical studies have been made on the effect of grooves perpendicular to and at an angle to the direction of air flow.[16] Liepmann[14] showed that the velocity profiles in the wake of semi-cylindrical elements have an inflection point. Schlitchting[23] points out clearly that flow having such velocity profiles will be associated with a much lower

critical Reynolds number at transition than flow with velocity profiles having no such point of inflection.



Velocity profile with no inflection point.



Velocity profile with an inflection point.

It should be noted that transition does not occur at the point of instability of the boundary layer. The amplification of some disturbances begins at the point of instability and continues downstream leading to transition.(23)

The experimental study to be conducted in this thesis with the use of a flow channel is aimed at obtaining qualitative results with which to evaluate several methods of turbulence stimulation in the boundary layer on flat plates.

Four basic types of turbulence stimulating devices were selected for this study. They are pins, sand strips, grooves, and trip wires. The main purpose in the series of tests is to evaluate various geometrical patterns and/or number of stimulators under similar flow conditions.

A number of acrylic plastic panels were manufactured. These panels fit into an opening in one side of the flow channel. The panels are 12 inches long by 7 inches high and are 1/4 of an inch in thickness. A complete description of the test facility appears in Appendix A.

The various stimulating devices are located the same distance from the forward edge of each panel, three inches. This is to insure an equal value of distance for the calculation of the Reynolds number at the point of stimulation. Only the middle three inches of the six inch channel height of the panels was utilized for the placement of stimulating devices. The allowed margin of 1-1/2 inches at the top and bottom was left in order to separate the boundary effects from those caused by the stimulating devices.

The array of pins and their number and size are listed in Table I. The proposed tests will allow a qualitative comparison of the effect on turbulence stimulation of projected area, projection distance into the fluid (k), diameter of pins (d), and d/k ratios.

The sand strips were made up of double-sided tape and medium coarse sand. The arrays of sand strips to be tested are listed in Table I.

The arrays of grooves are listed in Table I. The first two arrangements may possibly correlate with the work of Loftin[16], while the latter three will extend his investigation. It is expected that some knowledge will be gained on the effect of these groove arrangements on the formation of vortices.

The trip wire arrays and the diameters of the trip wires are given in Table I. It should be noted that the distance

between the face of the test panel and the trip wire can be varied over a wide range. It will be possible to observe what positions result in the shedding of vortices. These vortices should cause a rapid transition of the boundary layer from laminar to turbulent.

The use of this test facility will eliminate some of the variables present in the evaluation of turbulence stimulators on ship models.

1. A pressure gradient in the direction of flow can greatly affect the point of instability in laminar flow.[1,23] The pressure gradient along the length of a test panel can be assumed to be zero.

2. The condition of the surface of a test panel is uniform.

3. The degree of free stream turbulence can be easily ascertained by visual means. This turbulence can be controlled within certain limits.

4. The transmission of vibration to a test panel from outside sources is negligible.

TABLE I

Array of Stimulators on Test Panels

Note: The distance from the forward edge of the plate to the stimulators is three inches.

PINS Arranged in vertical line.

Panel No.	Diameter (in)	No. of pins	Projected Area of stimulation (in^2)	Spacing Center to center (in)
1	Smooth panel without stimulating devices.			
2	1/4	4	Can be varied	3/4
3	1/4	2	"	3/2
4	1/8	8	"	3/8
5	1/8	4	"	3/4
6	1/16	16	"	3/16
7	1/16	8	"	3/8

SAND STRIPS

Panel No.	Orientation	No. of Strips	Length (in)	Height (in)	Flat Area of stimulation (in^2)	Spacing Center to center (in)
8	Horizontal	3	1/2	1/4	3/8	1
9	Vertical	4	1/8	3	3/2	3/4
10	Horizontal	4	3	1/8	3/2	3/4

GROOVES Depth equal to 1/4 inch.

Panel No.	Orientation	No. of Grooves	Length (in)	Height (in)	Flat Area of stimulation (in^2)	Spacing Center to center (in)
11	Vertical	1	1/4	3	3/4	--
12	Horizontal	3	1	1/4	3/4	1
13	Cubical	3	1/4	1/4	3/16	1
14	"X" formation	1	1-5/8	1/4	3/4	--

TRIP WIRES

Panel No.	Orientation	Diameter (in)	Projected area of stimulation (in^2)	Remarks
15	Vertical	1/16	3/16	Spacing between panel and trip wire can be varied.
16	Vertical	1/8	3/8	

PROCEDURE

The development of the design of the apparatus as well as its description are included in the Appendix.

The procedure itself is rather uncomplicated. The system which is shown in Figures I through IV was charged with a dilute suspension of hectorite. The test panel was inserted in the positioning slots in the test channel. The edges of the test section were then made watertight with beeswax. Next the double refracting solution was continuously circulated through the test channel. The circulation was from the receiving tank to the pump, to the stilling section, through the test section and back to the receiving tank. Both the pump controlling rheostat and the channel gating were adjusted so as to produce a fairly wide range of flow velocities (from just above no flow to 2.0 feet/second). A field of circularly polarized light was created. This light showed the shear patterns which were set up within the fluid as it streamed past the stimulators. After several observations of test panels at various rates of flow, it was determined that 0.8 feet/second was a good average velocity for the conduct of the tests. Accordingly all panels were tested at this

velocity and photographs were taken of the created turbulence. In addition, the flow velocity was varied from low speed to high speed and the condition of flow both at the test section and farther downstream were observed. These latter observations were made using white light from a photoflood lamp in conjunction with two polaroid sheets which could be placed on opposite sides of the channel. In this manner the flow throughout the length of the channel was interpretable. The results of the tests are described in the following section.

RESULTS

The basis of the design and the construction of the test facility are described in Appendix A. The facility itself is shown in Figures I through IV.

The results of the tests conducted in conjunction with this thesis consist of a series of photographs which show the degree of turbulence stimulation effected by different types and arrangements of stimulators. These photographs, which are records of the tests, are itemized in Table II which follows.

TABLE II

Photographic Results

Note: Average velocity of fluid is 0.8 feet/second unless otherwise noted.

APPARATUS

Figure Number	Description
I	Test facility
II	Optical arrangement
III	Stilling section
IV	Typical test panels

PINS

Figure No.	Panel No.	(d) Diameter (in)	No. of Pins	(k) Distance projecting into fluid (in)	Projected area of stimulation (in^2)	$\frac{(d)}{(k)}$
V	1	Smooth panel without stimulating devices.				
VI	2	1/4	4	1/8	1/8	2
VII	4	1/8	8	1/8	1/8	1
VIII	6	1/16	16	1/8	1/8	1/2
IX	3	1/4	2	1/4	1/8	1
X	5	1/8	4	1/4	1/8	1/2
XI	7	1/16	8	1/4	1/8	1/4
XII	2	1/4	4	1/4	1/4	1
XIII	4	1/8	8	1/4	1/4	1/2
XIV	6	1/16	16	1/4	1/4	1/4

SAND STRIPS

Figure No.	Panel No.	Orientation	No. of strips	Length (in)	Height (in)	Flat Area of stimulation (in^2)
XV	8	Horizontal	3	1/2	1/4	3/8
XVI*	8	Horizontal	3	1/2	1/4	3/8
XVII	9	Vertical	4	1/8	3	3/2
XVIII	10	Horizontal	4	3	1/8	3/2

* Average velocity of fluid is 2.0 feet/second.

TABLE II

(continued)

GROOVES

Figure No.	Panel No.	Orientation	No. of grooves	Length (in)	Height (in)	Flat Area of stimulation (in^2)
XIX	11	Vertical	1	1/4	3	3/4
XX	12	Horizontal	3	1	1/4	3/4
XXI	13	Cubical	3	1/4	1/4	3/16
XXII	14	"X" formation	1	1-5/8	1/4	3/4

TRIP WIRES

Figure No.	Panel No.	Diameter (in)	Distance from panel to inner edge of wire (in)
XXIII	15	1/16	Zero
XXIV	15	1/16	0.02
XXV	15	1/16	0.125
XXVI	16	1/8	Zero

Figure II

Figure I

Figure III

Figure IV

Figure V

Figure VI

Figure VII

Figure VIII

Figure IX

Figure X

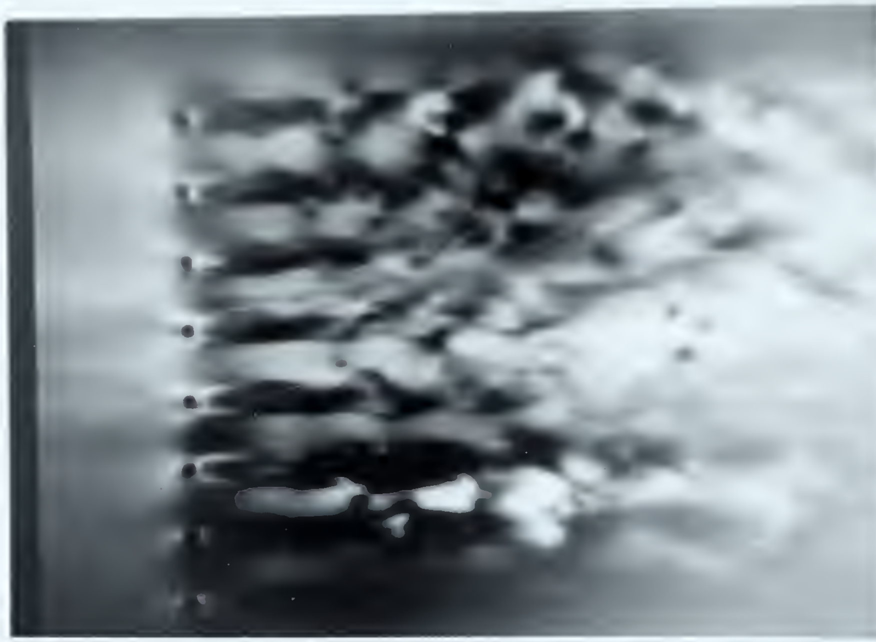


Figure XI

Figure XII

Figure XIII

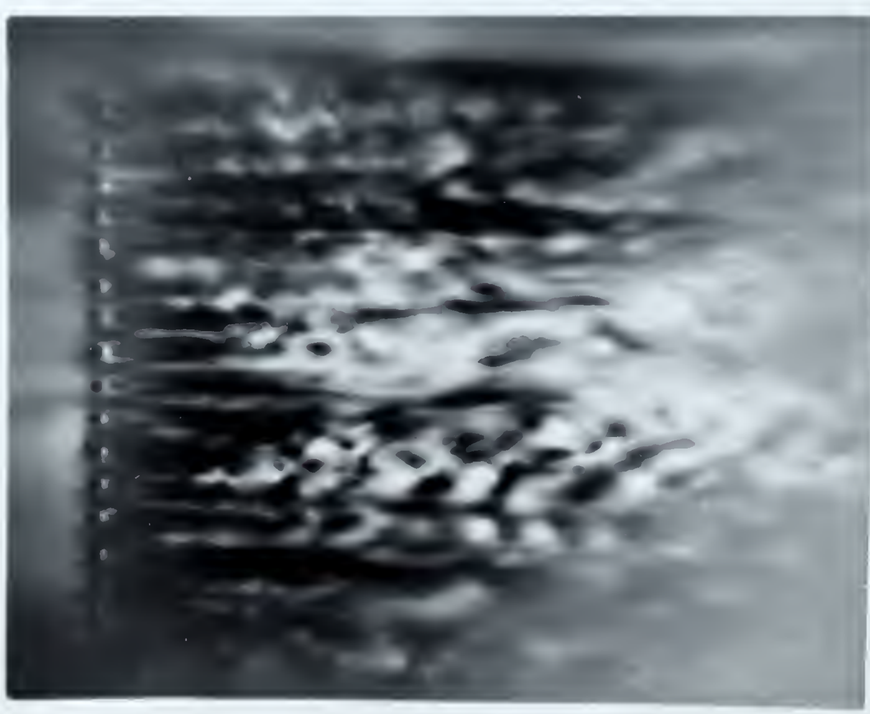


Figure XIV

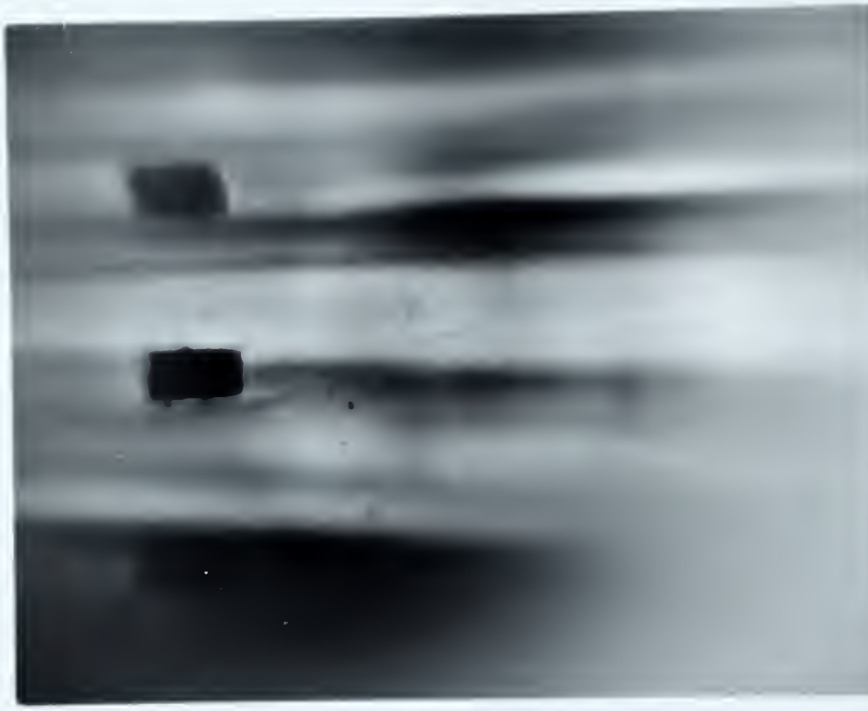


Figure XV

Figure XVI

Figure XVII

Figure XVIII

Figure XIX

Figure XX

Figure XXI

Figure XXII

Figure XXIII

Figure XXIV

Figure XXV

Figure XXVI

DISCUSSION OF RESULTS

Each type of stimulator first will be considered separately. Then all types will be compared with each other. The first illustration, Figure V, is that of flow of 0.8 feet/second velocity through the channel with no stimulator present. This photograph is included so as to provide a basis for evaluating the shear conditions shown in subsequent photographs with respect to the "zero turbulence conditions".

PINS

The pins in the various arrangements are shown as Figures VI through XIV. The first three illustrations show pin arrangements in which (k), the length of the pin projection into the stream, was 1/8 inch, and the total projected area* was 1/8 square inches.

The photographs show that some turbulence was created by the pins. However, the wakes created were not of sufficient magnitude to interact with adjacent wakes and cause transitional or turbulent flow.

The next three tests were those in which the total projected area of all pins was again 1/8 square inch;

---

* The area seen when looking toward the pins from the direction of flow.

however, (k) was increased to 1/4 square inch. Fairly turbulent wakes are evident in all pictures. But only in the case of the eight, 1/16 inch diameter pins do the wakes interact sufficiently to cause a transition to turbulent type flow.

In the last three figures the projection length was kept at 1/4 inch, but the projected area was increased to 1/4 square inches. Turbulent flow was caused in all three instances. Coverage on the total height is better with the sixteen, 1/16 inch diameter pins. However the degree of turbulence created appears greatest (albeit not markedly so) for the eight, 1/8 inch diameter pins.

A comparison between Figures XI and XIII shows that the eight, 1/16 inch pins having a projected area of only one half that of the eight, 1/8 inch pins is almost as effective in creating turbulence. Therefore, it may be surmised that the following criteria are important in designing pin-type stimulator arrays.

First the pin must project far enough into the stream so as to create a turbulent wake which expands somewhat as it proceeds downstream. Secondly, pins must be so spaced that the adjacent turbulent wakes interact and supplement each other so that a breakdown of flow is occasioned.

In general, a moderate number of small diameter pins produce the best stimulation per unit of parasitic drag.*

SAND STRIPS

The next series to be discussed is the sand strip series. This series is shown in Figures XV through XVIII.

Initially three arrangements were chosen. No turbulence is visible in XV (the first of the three initial arrangements) at the standard test velocity. At a higher rate of flow (2.0 feet/second) the effect of the sand strips in agitating the higher energy streams is discernible, XVI. Because of the limited effect shown in these tests the surface area of the strips was increased in anticipation of noticeably greater turbulence stimulation. The greater area array was first tested in a vertical orientation, XVII, and next in a horizontal orientation, XVIII. From these tests, it is concluded that a small amount of turbulence is created by the former. Furthermore, this turbulence first appears somewhere between the second and third strips. At the higher velocity of flow a very moderate amount of turbulence showed up at a point about three inches aft of the trailing edge of the stimulators. A somewhat lesser amount of agitation was noted in tests of the latter arrangement at both the standard and the high speeds.

---

* Since parasitic drag, without serious error, can be considered a direct function of projected area.

The conclusion is that sand strips are not too effective in inciting turbulence especially at lower velocities of flow. This same conclusion has been reached by others.[4,20] Of the two arrays, XVII and XVIII, it appears that the series of vertical strips is somewhat better than the series of horizontal strips. These conclusions are based on visual observations made at the higher rate of flow.

GROOVES AND CAVITIES

The series of grooves and cavities is next considered. Figures XIX through XXII pertain.

That grooves and cavities are ineffective in producing turbulence stimulation can be seen from these photographs. Even when streams of higher velocity gradient flow (distinguishable as black nearly horizontal lines) cross the depressions, no stream turbulence is created. That these higher energy streams do cause an agitation within the depressions (note the dark areas in the illustrations) is evident. However, these disturbances are not propagated out into the stream.

TRIP WIRES

The last and apparently the most effective series of stimulators employed trip wire devices. Reference is made to Figures XXIII through XXVI.

The 1/16 inch rod was placed in the following positions: flush against the test panel, XXIII; .02 inch out from the panel, XXIV; 1/8 inch out from the panel, XXV; and 1/4 inch out from the panel. The latter position is just about mid-channel. The optimum position for the trip wire was found to be 1/8 inch away from the wall. With this arrangement the greatest degree of turbulence, with regard to all of the stimulator types and arrays, was obtained. The projected area of a three-inch length of wire is 3/16 square inch.* This area is midway between the areas of XI and XIII. In addition to the foregoing tests, a 1/8-inch diameter wire was mounted flush against the test plate, XXVI. While having twice the projected area of the 1/16 wire, the 1/8-inch wire was not as effective in causing turbulence as the former when the former was located at its optimum position.

Here, again, the size of the stimulator governs the size and growth characteristics of the wake, and these in turn determine the optimum location of the device with respect to the boundary and hence the boundary layer. What remains to be determined is how the degree

---

* It can be seen that the trip wire located in the stream and the projecting pins which have large heads are not dissimilar in form. In fact, it may be said that a row of such pins are a form of an interrupted trip wire.

of turbulence varies with other size wires in various locations with respect to the boundary. Perhaps a smaller diameter wire will produce equally good turbulence.

These tests occasion a questioning of the point of view that a trip wire must be affixed completely to a model hull. The assertion is made that unless a complete attachment is made that the boundary layer will be reestablished and turbulence will not be created.(15) The foregoing tests strongly suggest that the optimum location of a trip wire be at a specific distance (dependent upon the size of the trip wire) from the model hull.

RECOMMENDATIONS

The desirability of expanding the tests is established by the interesting indications alluded to previously. Suggestions for the types of tests which are needed are given below.

SAND STRIPS - Whether or not a vertical strip of certain width creates better turbulence if the area is concentrated, or if the area is divided into several strips is of interest. Also of note is how the spacing of these strips effects the degree of turbulence stimulation.

PINS - It is desirable to test single pins of various diameters and of various projection depths to determine the size of their wakes. From this information an estimate of the most effective pin arrangement can be made, and the array can be tested. A further determination would be what is the best vertical arrangement - all in one row or staggered in several rows.

TRIP WIRES - A wider range of sizes of trip wires at various projections into the stream should be tried.

The facility may be used for the study of other flow problems. One such problem is the question of whether or not boundary layer control may be achieved by boundary layer suction. This problem is described in the following paragraphs:

The technique of reducing ships roll by the use of fin stabilizers has been notably successful. Therefore it is logical that fin stabilizers be used to ameliorate pitching motions. However, a practical difficulty of excessive ship vibrations has temporarily thwarted increased utilization of such a technique. These vibrations are likely caused by breakdown of flow across the fins. The feasibility of increasing the angle of attack before breakdown occurs by means of boundary layer suction has been suggested by the results of reference (19).

The experimental investigation of boundary layer control by means of boundary layer suction will require the construction of a hollow fin. This fin can be oriented at different angles of attack to a turbulent flow. Boundary layer suction can be applied at various places around the fin. Thus the effect of the boundary layer suction on the angle of attack at which flow breakdown occurs can be studied. Of course a model fin operates in lower Reynold's number flow than does the ship and for this reason scale effects are present. These scale effects prevent direct interpretation of results. However, the percentage change of characteristics should have an important qualitative significance.

Another study of significance would be the study of flow around various condenser tube arrangements. An investigation of such a nature should enable a determination of the best arrangement for the most effective degree of heat transfer.

Two improvements in the apparatus may be mentioned. A certain amount of upstream turbulence is present, especially at the higher velocities. This turbulence, while not destroying the effectiveness of the facility, is nonetheless somewhat distracting. Therefore, it is suggested that a grid (something like a symmetrical

honeycomb) be inserted in the inlet end of the stilling section.

The second recommendation for improving the facility is the result of the varying intensity of the light source across the test section. It is felt that a diffused light source of a greater intensity would improve the distribution of light for better photographic recording.

CONCLUSIONS

1. The test facility affords a means for the visualization of flow patterns using the streaming double refraction properties of dilute suspensions of hectorite.

2. It is strongly suggested that the trip wire optimally located is the best of the types of turbulence stimulators tested.

3. It is suggested that a moderate number of small diameter pins possesses good turbulence stimulating characteristics.

4. It is further suggested that a series of vertical sand strips is at least as effective in stimulating turbulence as is an array of horizontal strips. However, sand strips are less effective than trip wires or pins in stimulating turbulence.

5. It is rather clearly shown that grooves and cavities are not effective in producing turbulence in a water-type medium.

RECOMMENDATIONS

1. Extend the series of tests of turbulence stimulators in order to completely determine the size and location of the most effective stimulating device.

2. Conduct other studies which are amenable to qualitative analysis; such as, (a) the investigation of boundary layer control on hydrofoils by means of boundary layer suction, and (b) the investigation of arrangements of tubes in a heat exchanger for optimum heat transfer.

3. Improve the facility by incorporating a turbulence stilling grid in the stilling section.

4. Improve the photography by employing a diffused light source of greater intensity.

APPENDIX

A. Design and Construction of Facility.

B. Preparation of the Hectorite Suspension.

C. Photography.

D. Literature Citations.

APPENDIX A

Design and Construction of Facility

The principal aim of this thesis was to design and construct a permanent facility which will permit the visualization of fluid flow past two-dimensional forms. A basic idea was to utilize as far as possible equipment already available within the Department of Naval Architecture and Marine Engineering. Additionally, the test facility cost was to be held to a moderate amount.

In the design and construction of the test facility, two primary design criteria had to be met. The first was that the flow entering the observation or test area should be laminar flow in order to afford the best conditions for interpretation of the flow patterns. The second was that the materials used in the construction of the test facility must be inert to the action of solutions of hectorite. One disadvantage in using such a solution is that the presence of dissimilar metals in contact with the solution will result in electrolysis. This electrolysis causes a gelation of the hectorite at the negative electrode. The presence of corrosion products of metals also has the same effect on the solution. Brass and stainless steel are relatively inert to the action of dilute solutions of hectorite.

Polariscope

The polariscope located in the Ship's Structure Laboratory, Building 41, M.I.T., served as an essential part of the test facility.

This polariscope was slightly modified to suit better the needs of the experimental studies carried out in this thesis. The entire polariscope assembly was placed on one optical bench. The optical system used with this facility is as follows: A light-source (mercury-vapor lamp), collimating lens, a polarizer, quarter-wave plate, test channel, combination quarter-wave plate and analyzer, collimating lens and the camera. It should be noted that the light source holder was reversed in orientation and the protective hood removed. Additionally, the small reflector was replaced by a larger parabolic reflector. The reason for these changes was to increase the size and intensity of the light field so that better photographic recording of flow patterns could be made.

The collimating lens was placed between the light source and the polarizer to convert the divergent light rays into parallel rays of light prior to their entering the polarizer. The polarizer and analyzer with their associated quarter-wave plates were orientated with respect to one another to produce circularly polarized

light with a light field. The purpose being to obtain the maximum amount of light through the optical system. In relation to a plane polariscope the circular polariscope allows more light to be transmitted and causes the orientation of the polarizer to be independent of the orientation of the analyzer.[13]

The collimating lens located between the analyzer and the camera lens concentrates the parallel rays of light leaving the analyzer in to a beam of light at the camera lens. This allows the camera lens to transmit the maximum amount of available light to the film.

The theory and use of polarized light and the polariscope has only been briefly covered in this thesis. Anyone desiring further information is referred to reference (13) or to any standard text on the subject.

Stilling Section

This component of the test facility was designed and constructed to still (reduce) turbulence in the fluid prior to its discharge into the test channel. The stilling section was constructed in the Model Shop of the Department of Naval Architecture and Marine Engineering.

The following are the characteristics which should be incorporated in the stilling section:

1. The materials used in the construction of the stilling section must be inert with respect to solutions of hectorite.

2. The structure must have sufficient strength and rigidity to withstand the pressure head applied.

3. The inside surfaces and joints must be as hydraulically smooth as possible to prevent turbulence stimulation.

4. The cross sectional area must be of such a size and shape to give a Reynolds number low enough to result in the damping out of turbulence present in the entering fluid.

5. The fluid flow leaving the stilling section must have a rectangular shape of the same dimensions as that of the inside dimensions of the test channel.

6. The fluid flow leaving the stilling section should have a zero velocity gradient and possess no boundary layer at the retaining walls.

The stilling section was constructed from two layers of glass cloth impregnated with an activated polyster resin.

The complete assembly consists of several components, each of which was formed on a wooden mold and then joined together with additional pieces of glass cloth and resin.

There are two separate sections of equal length which are joined by a flanged connection. These flanges are reinforced with plywood backing pieces and separated by a neoprene gasket. The connection was completed by using brass bolts and wing nuts. The stilling section has an overall length of three feet and an area section of 7 inches by 7 inches. The prediction of the Reynolds number is given in the appendix under calculations.

The inside surfaces were made smooth with fine sand paper or filled in with activated resin. The surfaces were surprisingly very smooth due to the care used in the preparation of the surfaces of the wooden molds. Very little retouching was necessary. The outside surfaces were coated with shellac to cover any air holes.

The use of the described construction material and the procedures outlined above resulted in a design meeting the required characteristics listed as 1 through 4. The following paragraphs serve to show how the other remaining design requirements were met.

The exit section was so formed that the shape of the flow leaving it conformed exactly with the inside dimensions of the test channel. The exit section is

approximately three inches in length. It is so formed that there is a smooth convergence of the horizontal and vertical dimensions between the stilling section proper and the entrance to the test channel. This causes convergent flow with the establishment of a nearly uniform velocity gradient across the exit section and the elimination of a boundary layer at the retaining walls in the converging section. Thus it can be assumed that the reestablishment of a boundary layer will occur in the vicinity of the entrance to the test channel.

The inlet of the stilling section has an outer diameter of $1\frac{1}{2}$ inches and is circular in shape. The inlet was made larger than necessary in order to decrease the velocity of the flow entering. It is assumed that a lower velocity of entrance would result in a lesser penetration of the stilling section by the entering turbulent stream.

The exit section was connected to the test channel entrance by means of a flanged joint. This flange was so designed that the exit section perimeter contacted the test channel forming a smooth transition. A neoprene gasket formed a seal outside this contact area but not between these surfaces. The flanges were bolted together, using brass bolts and wing nuts.

Test Channel

In designing the test channel, it was necessary to have a small depth of flow along the optical observation axis. This results in an approximation of two dimensional flow. If a large depth were used, the greater superposition of flow lines would increase the difficulty of the interpretation of the flow patterns. Additionally, the test channel must be transparent.

The test channel was designed by the authors and constructed by Forest Products, Inc., Cambridge, Mass. The inside dimensions of the channel are approximately 6 inches in height, 1/2 inch in depth, and 4 feet in length. The entire channel is constructed of clear acrylic plastic of 1/4-inch thickness, except for the flanges which are 3/8-inch in thickness. The sides are sealed into grooves milled in the top and bottom sections. At the forward left hand side there is located a removable panel 12 inches in length. This panel is undercut by 1/8-inch by 1/8-inch on three edges. These undercut edges dovetail into matching portions of the channel. The top edge of the panel can be made water-tight, by clamping onto the flange located on the channel. A gasket is inserted between the surfaces. The other three edges are further sealed

with beeswax. There are approximately eighteen of these panels available for the conducting of tests.

The regulation of fluid flow was accomplished by two methods. The pump motor is equipped with a rheostat for controlling the discharge of the pump. The other method of control is a vertical sliding gate located in the after end of the test channel. Its position regulates the discharge and, hence, the velocity of the fluid in the channel. This control gate was located in this position rather than forward of the test section to avoid the formation of additional turbulence in the fluid forward of the test section. It was located well after the test section to avoid any influence of its action on the flow past the test section.

The type of material used in construction, clear acrylic plastic, was selected because it has the following advantageous properties:

1. Inert with respect to solutions of hectorite.

2. Highly transparent.

3. Ease of machining and repair.

4. Almost perfect optical and physical homogeneity.

5. High tensile strength.

6. High fringe constant.*

The measurement of velocity can be accomplished by several methods. The movement of visible objects can be timed in the channel. The quantity of fluid discharged in a period of time can be measured or a velocity transverse of the channel can be made with a pitot tube. The test facility has available a 1/8-inch stainless steel pitot tube.

Sump

The sump at the end of the test channel is a twenty-gallon polyvinyl container. A rubber hose is attached to the bottom with the aid of glass cloth impregnated with a polyester resin. All of these materials are inert to solutions of hectorite.

---

* The units of fringe constant are lbs./in. per order of interference. Any stress in the material will produce lines of constant shear stress in the material. When observed with polarized light, these lines appear as dark bands within the material and are called isochromatics. The lower the fringe constant of the material the greater is the number of these bands which will be produced by a given stress. The presence of a great number of these bands would complicate the interpretation of the flow patterns produced in the channel.

The sump is located so that the centrifugal circulating pump has a positive head on it at all times.

Circulating Pump

The pump selected for circulating the solution is a model E-7 centrifugal pump manufactured by Eastern Engineering Co., New Haven, Connecticut. It is made of stainless steel and has an output capacity of nine gallons per minute at zero head. The driving unit is a 110V Universal motor. In addition, a rheostat is connected to the motor for the purpose of controlling the speed of the motor and thus the discharge rate of the pump.

The pump is connected to the stilling section inlet and to the sump by means of $1\frac{1}{2}$-inch four (4) ply rubber hose.

The calculations required in the design of this test facility are as given below:

Stilling Section - Reynolds Number (R')

Ref. (22)

v = Average velocity of fluid flow-feet/second

R = Hydraulic radius-feet

ν = Kinematic viscosity-feet^2/second

where,

ν = factor x viscosity of water - see ref. (6, page 212).

$$\nu = 1.88 \times 1.05 \times 10^{-5} \text{ feet}^2/\text{second.}$$

$$v = 0.05 \text{ feet/second.}$$

$$R = \frac{\text{area}}{\text{wetted perimeter}} = \frac{49/144}{28/12} = 0.146 \text{ feet.}$$

$$R' = \frac{4\,v\,R}{\nu} = \frac{4 \times 0.05 \times 0.146}{1.97 \times 10^{-5}}$$

$$R' = 1480$$

<u>Location of transition point on a flat plate</u>

Ref. (23)

$$R'_{x_{critical}} = 3.2 \times 10^5 \text{ (Flat Plate)}$$

$$R'_{x_{critical}} = \left(\frac{v\,x}{\nu}\right)_{critical}$$

$$x = \frac{3.2 \times 10^5 \times 1.97 \times 10^{-5}}{0.8}$$

x = 7.9 feet from test channel entrance.

Location of point of instability on a flat plate

Ref. (23)

$$R'_{x_{critical}} = 1.12 \times 10^5 \quad \text{(Flat Plate)}$$

$$R'_{x_{critical}} = \left(\frac{V\,x}{\nu}\right)_{critical}$$

$$x = \frac{1.12 \times 10^5 \times 1.97 \times 10^{-5}}{0.8}$$

x = 2.76 feet from test channel entrance.

The value of the Reynolds number calculated for the stilling section indicates that the proposed design will be effective in reducing the entering turbulence. All disturbences are damped when the Reynolds number is less than 2000 [23].

The calculations on the point of instability and transition points on flat plates indicates that these points will occur well after (downstream) of the location of the test panels. This calculation was based on the assumption that a panel in the channel side will have a boundary layer build up similar to that on a flat plate placed in a moving fluid. The boundary layer reestablishes itself at the entrance to the test channel.

APPENDIX B

The Preparation of the Hectorite Suspension

The hectorite was obtained from R.T. Vanderbilt Company of New York, N.Y. The clay is sold under the trade name of "Veegum T". This clay is a purified form of hectorite which contains about 6% of lime (as calcium oxide) as against about 25% in unpurified clays. The average chemical analysis of this product is given in reference (30).

The procedure for preparing a suspension of hectorite in water is to be described. First distilled water is heated to as close to 200°F as is physically practicable. Enough hectorite to produce a 5% suspension is then gradually added to the water. During the addition of the clay to the water the two are mixed intimately together by means of a high shear mechanism. The dispersator and the other facilities of Room 12-132 at M.I.T. were used with the kind permission of Mr. James P. Collins of the Civil Engineering Department.

After the dispersion had been made, the suspension was diluted to the desired concentration and permitted

to hydrate for a minimum of 4 hours. A dilute solution of hectorite fully hydrated should be fully stabilized. If flocculation occurs certain additives may be used to stabilize the suspension[29].

The solution should be stored in and used with certain inert materials. A list of these materials is given in reference (29).

APPENDIX C

Photography

The pictures presented in this thesis were taken with a Graphic View II camera. This camera has a 14.7 Graflex Optar 135 mm. lens. All the pictures were recorded on 4" x 5" Kodak Royal Pan film.

The optical arrangement for taking the pictures of the test panels was as follows: A light-source, collimating lens, a polarizer, quarter-wave plate, test channel, combination quarter-wave plate and analyzer, collimating lens and the camera. These components, with the exception of the type of camera, comprise the polariscope located in the Ship's Structure Laboratory, Building 41, at M.I.T. The entire assembly was placed on one optical bench for easy alignment.

The light source was a mercury-vapor lamp with a parabolic reflector. The components of the polariscope were arranged to produce a circular polariscope with a light field. The pictures of the actual tests were taken at 1/400 of a second.

The pictures were composed to include the flow prior to the stimulating devices, the flow following the devices, and an area above and below these devices. The camera was arranged to record pictures with a magnification factor equal to one, i.e., all the pictures of the test panels in use are of actual size. The development of the pictures and prints was carried out in the darkroom of the Ship's Structure Laboratory. The prints were produced by the method of projection printing. Standard methods and procedures were followed.

APPENDIX D

Literature Citations

1. Allan, J.F. and Conn, J.F., "Effect of Laminar Flow on Ship Models," Trans. Instn. Naval Architects, vol. 92, 1950.

2. Allan, J.F. and Huges, G., "Turbulence Stimulation on Ship Models," Trans. Soc. Naval Architects and Marine Engineers, vol. 59, 1951, pp. 281-314.

3. Breslin, J.P. and Macovsky, M.S., "A Study of Rods as Stimulators of Turbulence in Boundary Layers," Progress Report on Research in Frictional Resistance, TMB Report 726, September 1950, pp. 35-38.

4. Breslin, J.P. and Macovsky, M.S., "Effects of Turbulence Stimulation on the Boundary Layer and Resistance of a Ship Model as Detected by Hot Wires," TMB Report 724, August 1950.

5. Charters, A.C.,Jr., "Transition Between Laminar and Turbulent Flow by Transverse Contamination," NACA Technical Note No. 891, March 1943.

6. "Clays and Clay Minerals," National Academy of Sciences-National Research Council, Publ. 456, 1955, pp. 212, 240-249.

7. Couch, R.B. and Hinderthan, W.B., "Experimentation to Develop Suitable Methods for Stimulating Turbulent Flow About Ship Models," Progress Report on Research in Frictional Resistance, TMB Report 726, September 1950, pp. 25-34.

8. Davidson, K.S.M., "Some Experimental Studies of the Sailing Yatch," Trans. Soc. Naval Architects and Marine Engineers, vol. 44, 1936, Appendix I.

9. Dewey, D.R., II, "Visual Studies of Fluid Flow Patterns Resulting from Streaming Double Refraction", Sc.D. Thesis, M.I.T., 1941.

10. Dickerson, L.L.,Jr., "Streaming Double Refraction Applied to the Photographic Analysis of Fluid Motion", Sc.D. Thesis, M.I.T., 1942.

11. Fage, A., "The Smallest Size of a Spanwise Surface Corrugation which Affect Boundary-Layer Transition on an Aerofoil," Aeronautical Research Committee, Reports and Memoranda No. 2120, January 1943.

12. Hancock, C.H., "The Equipment and Methods Used in Operating the Newport News Hydraulic Laboratory," Trans. Soc. Naval Architects and Marine Engineers, vol. 56, 1948, pp. 40-41.

13. Hete'nyi, M., "Handbook of Experimental Stress Analysis," John Wiley & Sons, Inc., New York, N.Y., 1950, pp. 829-965.

14. Liepmann, H.W., "Investigation of Boundary Layer Transition on Concave Walls," NACA Report W-87 (originally issued as ACR No. 4J28, February 1945).

15. Liepmann, H.W. and Fila, G.H., "Investigations of Effects of Surface Temperature and Single Roughness Elements on Boundary-Layer Transition," NACA Report No. 890, 1947.

16. Loftin, L.K.,Jr., "Effects of Specific Types of Surface Roughness on Boundary-Layer Transition," NACA Report L-48 (originally issued as ACR No. L5J29a, February 1946).

17. "MACALOID", The Inerto Company, San Francisco, California, 1957.

18. McAdams, W.H., "Heat Transmission," McGraw-Hill Book Company, Inc., New York, N.Y., 1954, pp. 149-159.

19. Moyer, D.R. and Michaels, R.J., "Hydrodynamic Similar Roll Stabilization Fins for Ship Model Tests," M.I.T. Thesis, Cambridge, Mass., 1958.

20. Nevitt, C.R., "The Resistance of Trawler Hull Forms of 0.65 Prismatic Coefficient," Trans. Soc. of Naval Architects and Marine Engineers, vol. 64, 1956.

21. Rosenberg, B., "The Use of Doubly Refracting Solutions in the Investigation of Fluid Flow Phenomena," Report 617, DTMB, March 1952.

22. Rouse, H., "Elementary Mechanics of Fluids," John Wiley & Sons, Inc., New York, N.Y., 1946.

23. Schlitchting, H., "Boundary Layer Theory," Pergamon Press, New York, N.Y., 1955.

24. Schubauer, G.B. and Skramstad, H.K., "Laminar-Boundary Layer Oscillations and Transition on a Flat Plate," NACA Report No. 909, 1948.

25. Walker, W.P., "Detection of Laminar Flow on Ship Models," Trans. Instn. Naval Architects, vol. 91, 1949, pp. 220-236.

Correspondence in regard to thesis:

26. Letter from the late Robert T. Knapp, Professor of Hydraulic Engineering, California Institute of Technology dated 10/9/52.

27. Letter from J. Harold Wayland, Division of Engineering, California Institute of Technology, dated December 3, 1958.

28. Letter from Ray McAdam, The Inerto Company, San Francisco, California, January 29, 1959.

29. Letter from R.G. Shaler, The Inerto Company, San Francisco, California, February 20, 1959.

30. Letter from F.E. Hutchins, R.T. Vanderbilt Company, New York, N.Y., March 23, 1959.